Characterization of
Polymer Tantalum Capacitors

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ABSTRACT

This effort is the continuation of a three-phase task to characterize tantalum polymer capacitors. Phase 1 included the history of tantalum capacitors from wet to solid, an introduction and comparison between manganese dioxide (MnO_2) and polymer tantalum capacitors, a discussion on different polymer types, and some typical electrical characteristics.

Industry has moved away from wet tantalum capacitors due to limitations of the technology. One limitation of wet tantalum technology is the electrolyte used to be able to escape from the package resulting in the capacitor slowly failing open. Current military-grade wet tantalum capacitors have robust packages that prevent leakage, unless damage is caused during handling or soldering. They also have poor performance at low temperatures since the charge carriers become less mobile. One benefit of wet tantalum technology is its self-healing capabilities. Since the anode is always in electrolyte, new oxide forms easily (an environment similar to the original dielectric formation).

Solid tantalum technology offers some improvements over wet tantalum technology. They are smaller and exhibit better electrical performance. Solid tantalum capacitors are also self-healing, have less capacitance roll-off, and demonstrate lower dissipation factor (DF) and equivalent series resistance (ESR) [1].

Conducting polymer material has been introduced as a candidate to replace MnO_2. Polymers are more conductive than MnO_2 and have no ignition problems. These capacitors have even lower ESR and improved high-frequency performance, but higher leakage current. The low temperature deposition of the polymer during manufacture causes less damage to the dielectric compared to the high temperature conversion needed for MnO_2. However, polymer material is less thermally stable and starts to break down around 200°C. For higher rated voltages, the breakdown and life test advantages are reduced [1].

Phase 2 presented independent competitive electrical performance data, dielectric robustness data, and reliability data. Performance advantages demonstrated by the polymer capacitors from these tests greatly suggest they should be considered for high-reliability space applications. The claims of lower ESR and better stability of capacitance versus frequency and temperature were established. Electrical performance at temperatures of −55 °C was much superior to that of comparable MnO_2 technology. Tantalum polymer capacitors showed exceptional robustness against rapid charging above rated voltage, while some tantalum MnO_2 capacitors demonstrated higher breakdown voltages. Performance during the 85°C rated voltage life test of polymer versus MnO_2 technology was comparable, but tantalum polymer technology has not matured to the point of being routinely used in harsh operating conditions such as 125°C or high humidity situations [2].

Phase 3 is intended to conduct highly accelerated time-to-failure testing and develop acceleration models to predict performance at rated conditions. Tantalum polymer devices of several different voltage ratings will be tested and assessed. At this time, only data associated with devices rated at 4 V are presented.

1.0   INTRODUCTION

The focus of this project is assessing the lifetime of polymer tantalum capacitors at maximum rated conditions, noting distributions of failures in time, and studying the applicability of the Weibull grading method to tantalum polymer capacitors. Devices will be tested at several temperatures and voltages chosen specifically to reach wearout in a reasonable amount of time.

The goal is to develop an accurate acceleration model by focusing on accelerated life tests using elevated voltage and temperature conditions. A secondary goal is to compare two different manufacturers, Manufacturer A and Manufacturer B, to see if the acceleration models developed are similar. Each part type will be subjected to three various test voltages at three different temperatures. The temperatures 85°C, 105°C, and 125°C were chosen for the experiment. Applied test voltages for each temperature varied and were determined by scouting tests. The goal of scouting was to achieve sufficient voltage acceleration that all of the parts would fail in a reasonable amount of time.

Table 1-1 summarizes the capacitors chosen for evaluation. At this time, complete data are only available for the 220 µF, 4 V devices.

Testing was modeled after that described in [3]. Tantalum polymer capacitor failures in time should produce a lognormal time-to-failure distribution with a very steep slope indicating wearout instead of a shallow slope time-to-failure distribution as is typically produced by MnO_2 type capacitors.

Figure 1-1 is an example of time-to-failure data for B-case, 100 µF, 6 V devices taken from Figure 6 in [3]. It depicts data taken at a temperature of 105°C at several different voltage accelerations. It was expected that the D-case 4 V, 6 V, 10 V, and 16 V devices chosen for this experiment would behave in a similar fashion.

Table 1-1. Tantalum Polymer Capacitors

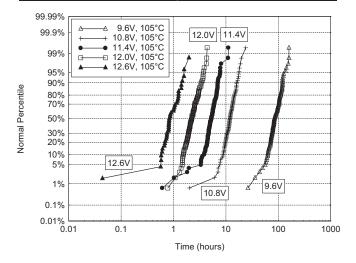| Capacitance (µF)	Rated Voltage (V)
220	4
330	6
100	10
47	16

Figure 1-1. Tantalum Polymer Lognormal Distribution Example [3]

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2.0   TIME-TO-FAILURE ANALYSIS

The 100 µF, 10 V polymer capacitors were the first to undergo accelerated life testing.

Figures 2-1 and 2-2 show data collected at a temperature of 85°C and a test voltage of 18 V for both manufacturers. It does not follow the expected trend and looks more like a Weibull plot of MnO_2 failures. Both tests were halted around 100 hours since they were not behaving as expected. This behavior suggests that a different failure mechanism is at work. This new and unexpected behavior needs additional investigation, which is outside the scope of this current task. All testing of the 100 µF, 10 V parts was stopped and testing of the 220 µF, 4 V parts commenced.
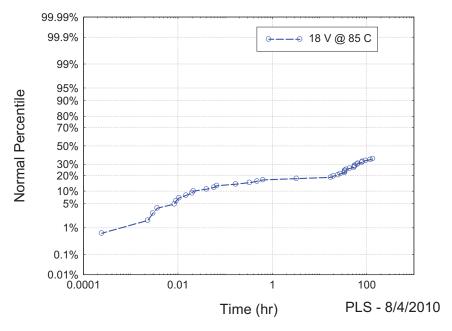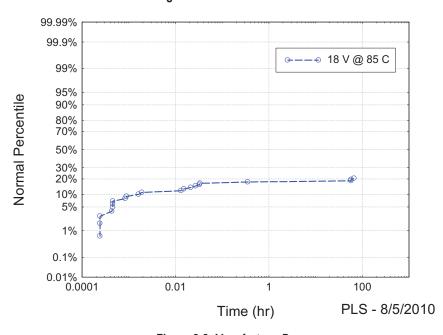
Figure 2-1. Manufacturer A

Figure 2-2. Manufacturer B

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At this time, only data for the 220 µF, 4 V capacitors are available for analysis.

Table 2-1 shows the chosen test voltages for each temperature and the resulting t_{50} times. The test voltages were chosen from scouting tests with the goal of having the highest test voltage produce t_{50} around 2 hours, the middle test voltage produce t_{50} around 10 hours, and the lowest test voltage produce t_{50} around 100 hours. The resulting t_{50} values were estimated from the time-to-failure data by using a best fit line for each of the time-to-failure distributions.

The 220 µF, 4 V capacitors made by Manufacturer A and tested at 85°C, behaved as expected as shown in Figure 2-3. Each test voltage resulted in a plot relatively parallel to the others at the fixed temperature.

Table 2-1. Testing Conditions and Resulting t_{50} Values

Manufacturer A: 220 µF, 4 V								
85°C			105°C			125°C		
V_{Test} (V)	t_{50} (hr)		V_{Test} (V)	t_{50} (hr)		V_{Test} (V)	t_{50} (hr)	
10	169		8.8	105		8.8	13	
10.8	46		9.6	33		9.2	8.6	
11.6	18		10.4	11		9.6	4.5	

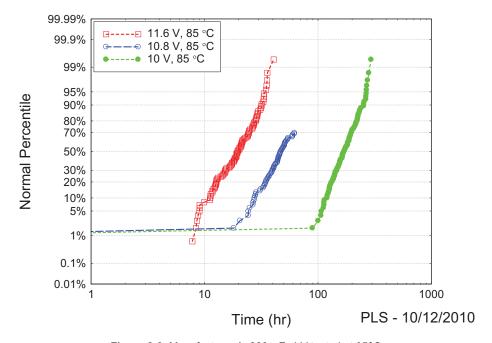| Manufacturer B: 220 µF, 4 V								
85°C			105°C			125°C		
V_{Test} (V)	t_{50} (hr)		V_{Test} (V)	t_{50} (hr)		V_{Test} (V)	t_{50} (hr)	
10.8	300		10	110		8.8	50	
11.6	13		10.8	26		9.2	28	
12.4	0.4		11.6	10		9.6	19	

Figure 2-3. Manufacturer A, 220 µF, 4 V tested at 85°C

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The time-to-failure data for Manufacturer B in Figure 2-4 are somewhat expected and somewhat not expected. The curves in Figure 2-4 almost follow the same trend as in Figure 2-3, but appear to have multiple sub-distributions within the same lot. This suggests that a larger sample size from a well-randomized population may be needed in order to generate a more accurate picture of what is going on. Also, the early time failure distributions initially display similar behavior as was seen in Figures 2-1 and 2-2 for the 10 V parts. This suggests that there may be more than one failure mechanism at work in the test at these test voltages.

Data for Manufacturer A in Figure 2-5 at 105°C seem to exhibit a more uniform relationship among the failure distributions generated at the different test voltages.
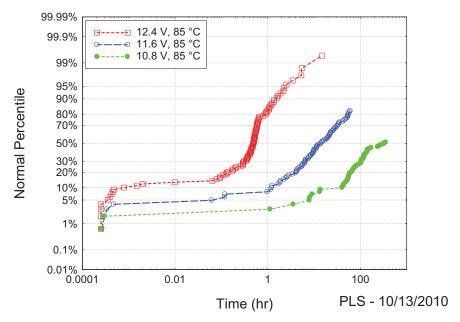
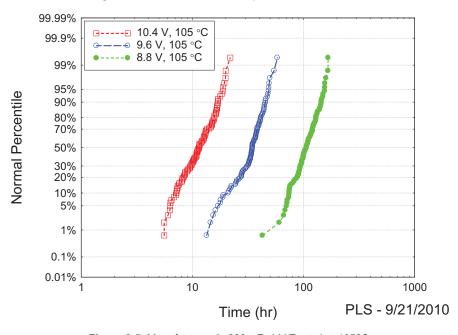**Figure 2-4.** Manufacturer B, 220 µF, 4 V Tested at 85°C

Figure 2-5. Manufacturer A, 220 µF, 4 V Tested at 105°C

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Figure 2-6 demonstrates more pronounced evidence of the multiple distributions within the lot for the times to failure of Manufacturer B at the test voltage 11.6 V. Generally, the times to failure decrease as the test voltage rises, as expected, but the shape of the distribution also changes with increasing voltage, which suggests introduction of a new degradation mechanism.

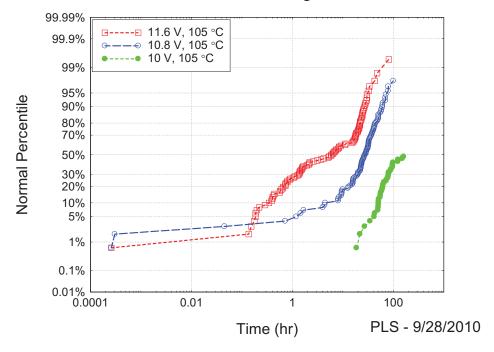Figure 2-7 for Manufacturer A shows similar results to Figures 2-3 and 2-5.

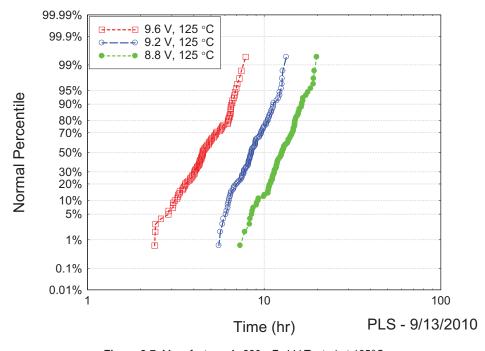**Figure 2-6.** Manufacturer B, 220 µF, 4 V Tested at 105°C

Figure 2-7. Manufacturer A, 220 µF, 4 V Tested at 125°C

Figure 2-8 data appear to reflect the typical tantalum polymer failure distributions that are expected with less strenuous voltage accelerations. The data have shallower slopes than those seen in the plots for Manufacturer A. The curves do not contain the bimodal distributions seen in Figures 2-4 and 2-6, which suggested that the voltage accelerations chosen for 85°C and 105°C were too harsh and likely introduced a new failure mechanism.
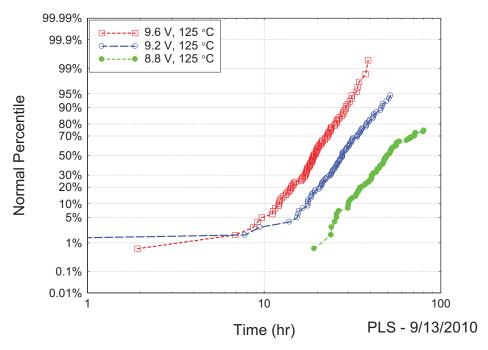

Figure 2-8. Manufacturer B, 220 µF, 4 V Tested at 125°C

3.0   ACCELERATION MODELS

The equation proposed by Prokopowicz and Vaskas shown in Equation (1) was chosen for the acceleration model [3].

$$A = \frac{t_1}{t_2} = \left(\frac{V_2}{V_1}\right)^{\eta} e^{\left[\frac{Ea}{k}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)\right]} \tag{1}$$

The formula can be broken down into two parts to calculate voltage acceleration and temperature acceleration separately. The voltage stress exponent (η) and activation energy (E_a) must be derived experimentally from time-to-failure data. Median life values (t_{50}) from the failure distributions are used for t_1 and t_2. The constant k is Boltzmann's constant, $8.62*10^{-5}$ eV/K [3].

The t_{50} times at the various temperatures and test voltages are plotted on a log-log scale in Figure 3-1 to linearize the power law form of voltage acceleration in Equation (1). This facilitates estimation of η, which is the voltage ratio exponent that predicts failure acceleration due to increasing test voltage.

The data in the voltage acceleration plot for Manufacturer A shown in Figure 3-1 are pretty well behaved. It is possible to project back to rated voltage fairly easily. The slopes of the lines generated by the t_{50} data points are similar and have a decreasing voltage ratio exponent (η) as the temperature rises. This response is consistent with the results published in [3].
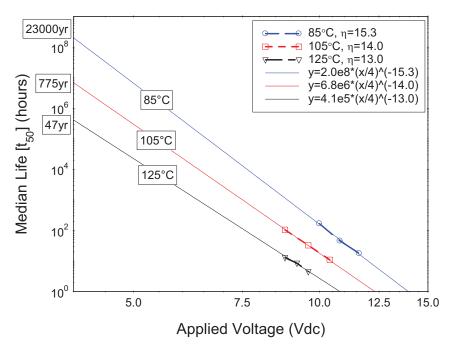
220uF, 4V Tantalum Polymer (Mfgr. A)
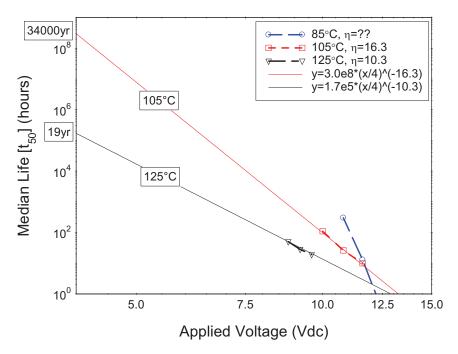

Figure 3-1. Manufacturer A Voltage Acceleration

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Figure 3-2. Manufacturer B Voltage Acceleration

In contrast, the data for Manufacturer B in Figure 3-2 are not as ideal. The 125°C data look fine at η of 10.3, but the slope for the 105°C data begins to get very steep at η of 16.3 and the data are questionable. The data for 85°C certainly do not support a meaningful extrapolation to lower test voltages. This means that in the effort to minimize test time, the test voltages were selected to be too high. The test voltages were too close to the oxide formation voltage and excite a new failure mechanism, which has a much higher voltage ratio exponent than the wearout mechanism that is dominant at or below rated voltage. The time-to-failure slopes are increasing as 12.4 V is approached. If 12.4 V were used at the temperatures of 105°C and 125°C, it is likely the same results would be observed. This is evidence that there are absolute limits to how much this testing can be accelerated.

Manufacturer A's t_{50} times are plotted versus inverse absolute temperature (1/T, with T in Kelvin) in Figure 3-3. This linearizes the Arrhenius expression for temperature acceleration so straight lines can be fit to the curves to estimate the activation energy in electron volts (eV) at various test voltages. Unfortunately, the same voltages at two different temperatures were only used two times (8.8 V and 9.6 V at 105°C and 125°C). A least squares line was fit to those points and the activation energy was found to be 1.35 eV at 8.8 V and 1.29 eV at 9.6 V. The higher activation energy at lower voltage is consistent with results seen in [3].

Fit lines could not be added to the other t_{50} data points because of these groups; no two tests were done at the same voltage and two temperatures. However, dashed lines with the same slope as the 9.6 V line show that the spacing between the lines is very consistent with the spacing of the test voltages. This is also consistent with the analogous temperature acceleration graph in [3].
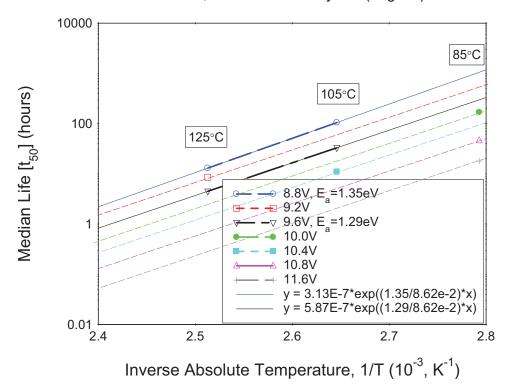
Figure 3-3. Manufacturer A Temperature Acceleration

A temperature acceleration graph for Manufacturer B was not plotted from the test data. The voltage acceleration graph was already severely compromised by the introduction of a new failure mechanism at high test voltages. It is unfortunate that a useful temperature acceleration model cannot be inferred from this data.

4.0   SUMMARY AND CONCLUSIONS

Accelerated life test data to date are presented for 220 µF, 4 V tantalum polymer capacitors. Testing did not progress as far as expected, but now the testing limitations are better understood, which will allow for further progress next year. Applicability of the Weibull grading method will also be assessed next year.

Accelerated life tests are designed to test at high voltages in order to predict behavior at low voltages. It is a delicate balancing act to accelerate conditions enough to produce meaningful wearout data in a short amount of time without introducing a completely different failure mechanism.

The results of the time-to-failure data of Manufacturer B highlight that caution must be taken when accelerating test conditions. The data obtained for Manufacturer B are not currently useful to establish an acceleration model. Subjecting the devices to such high voltages (12.4 V for a 4 V part) introduced a new failure mechanism. However, performing additional tests at lower test voltages should provide the basis for meaningful extrapolation to performance at lower application voltages. Also, it will be useful to observe the voltage acceleration plot curvature, which indicates onset of the new failure mechanism.

The data collected for Manufacturer A resulted in a very promising acceleration model that predicts very long life at rated voltage and 85°C. With suitable voltage derating, tantalum polymer technology could easily be used in appropriate high-reliability space applications.

5.0 REFERENCES

[1]   Reed, Erik K. *Characterization of Tantalum Polymer Capacitors: NEPP 2005.* Available at: http://nepp.nasa.gov/docuploads/0EA22600-8AEC-4F47-9FE49BAABEAB569C/ Tantalum%20Polymer%20Capacitors%20FY05%20Final%20Report.pdf

[2]   Reed, Erik K. *Characterization of Tantalum Polymer Capacitors: NEPP 2006,* JPL CL# 07-1924, October 9, 2007.

[3]   Paulsen, Jonathan L., Reed, Erik K., and Kelly, Jeffrey N., "Reliability of Tantalum Polymer Capacitors," *CARTS-Europe 2004*, Nice, France, Oct. 18–21, 2004, pp. 33–39.